Telescope for X-ray and Gamma-ray Studies in Astrophysics

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ABSTRACT

Imaging of X-rays has been achieved by various methods in astrophysics, nuclear physics, medicine, and material science. A new method for imaging X-ray and gamma-ray sources avoids the limitations of previously used imaging devices. Images are formed in optical wavelengths by using mirrors or lenses to reflect and refract the incoming photons. High energy X-ray and gamma-ray photons cannot be reflected except at grazing angles and pass through lenses without being refracted. Therefore, different methods must be used to image X-ray and gamma-ray sources. Techniques using total absorption, or shadow casting, can provide images in X-rays and gamma-rays. This new method uses a coder made of a pair of Fresnel zone plates and a detector consisting of a matrix of CsI scintillators and photodiodes. The Fresnel zone plates produce Moiré patterns when illuminated by an off-axis source. These Moiré patterns are deconvolved using a stepped sine wave fitting or an inverse Fourier transform. This type of coder provides the capability of an instantaneous image with sub-arcminute resolution while using a detector with only a coarse position-sensitivity. A matrix of the CsI/photodiode detector elements provides the necessary coarse position-sensitivity. The CsI/photodiode detector also allows good energy resolution. This imaging system provides advantages over previously used imaging devices in both performance and efficiency.

INTRODUCTION

In recent times, the need for X-ray imaging devices has been realized in astrophysics, solar physics, nuclear physics, medicine, and material science. In astrophysics, X-ray images can be used to study transients and X-ray bursts, as well as allowing broad spectrum maps of the skies. These high energy images can be matched with images in the optical range to give researchers more data for the study of the astrophysical phenomena. In solar physics, good X-ray images will allow the phenomena of solar flares to be studied more closely. X-ray crystallography is a valuable tool in material science. Good X-ray imaging devices would be beneficial in this field. The medical field also can benefit greatly from efficient X-ray imaging systems.

In the early 1960's, it was suggested that X-ray imaging could be done by shadow casting using coded masks.[1] The coded masks cast shadows of their patterns which can then be looked at to determine the arrangement of the sources. The coded mask should be such that the shadows cast by two sources have a low cross-correlation. The simplest of coded mask systems is a mask with a single hole[2]. This system directly provides an image of the illuminating sources, but to achieve good resolution, the hole must be small. This does not allow many photons to pass, thus causing count rates to be low. In order to solve the problem of low photon numbers, more random holes must be added.[3] Extracting an image then becomes more difficult.

Multiple plane imaging systems have also been suggested by various authors.[4,5] These systems have larger apertures and thus allow higher photon numbers. The shadows cast by bi-grid systems are also confused, but they lend themselves to easy deconvolution methods such as an inverse Fourier transform. Two types of bi-grid systems are rotating modulation collimators and phased stationary systems.[6] Rotating modulation collimators provide both good spatial resolution and can have a large aperture. However, they do not provide good time resolution. For the rotating modulation collimators to provide the sine and cosine components needed for the inverse Fourier transform, the grids must be rotated. This means that sources which vary rapidly with time will have some of the detail lost. The amount of spatial resolution depends on the spacing of the parallel bars of the grid and the distance between the grids.[7,8,9]

Two zone plates in tandem do not require rotation to provide the modulation of the sources. One example of a zone plate which can be used is a Fresnel zone plate. A Fresnel zone plate consists of concentric rings of alternating opaque and transparent material all having equal area. When this system is illuminated by a source, the zone plates cast shadows on the detector. These shadows form Moiré patterns which are parallel lines whose separation is proportional to the distance the source is located off the axis of the system.[1,5]

Methods and Materials

The use of Fresnel zone plates in a bi-planar imaging system requires several choices depending upon angular resolution needed, field of view, etc. The zone plates can be constructed to various specifications.(See table) The thickness of the plates is the first variable to be chosen. The thickness of the plate is somewhat dictated in certain energies by the requirement that alternate zones must absorb the incident photons. When considering the plates for use with X-rays, the thickness of the material must be such to stop these high energy photons.

Fresnel zone plate specifications
Radius of innermost zone $r_1 = 1$ cm
Number of zones in plate $N = 100$
Radius of n^{th} zone $r_n = r_1 \sqrt{n}$
Diameter of zone plate $d = 20$ cm
Width of outer zone $\Delta r_N = r_1^2/d = 0.05$ cm

The plate can be flat with a uniform thickness for all absorbing zones, or the plate can be tapered with the innermost zone being thicker than the outer zone. If the zones are of uniform thickness, the inner zones which have larger radii will allow photons to pass the zone plate at greater angles than the outer zones will allow. This will cause an unequal contribution to the coded image by the various zones. If the thickness of the plate varies, however, the angle at which each zone allows a photon to pass will be equal. A tapered design will allow the outer zones to contribute to the production of the coded image by limiting the angle of incidence which the inner zones will allow the photons to pass. Greater thickness for the middle zones will allow the zones on the edge to contribute equally. The thickness at the edge of the zone plate should be chosen such that a photon passing though the outermost zone of the top plate is able to interact with any of the zones in the lower plate. The thickness of each zone can be determined using the following relation to the thickness of the innermost zone:

$$h_n = \frac{[h_1 (\sqrt{n} - \sqrt{n-1})]}{\sqrt{2} - 1}$$

where h_n is the thickness of the n^{th} zone and h_1 is the thickness of the innermost zone.

It is important to have the outermost zones of the plate contribute to the formation of the image because the angular resolution is a function of the size of the smallest zone.

$$\theta = \tan^{-1} (\Delta r_N/D)$$

where D is the separation between the two zone plates. Therefore, for the specifications given above, an angular resolution of approximately 1 arcminute is possible. It is not necessary for the detector to resolve the smallest zone of the zone plates as is necessary in single zone plate imagers. In bi-planar systems, the detector must only be capable of resolving the produced Moiré patterns. Since the size of the smallest zone determines the angular resolution, the value of the <u>tandem</u> Fresnel zone plate system is that it is not necessary for the detector plane for this system to have high spatial resolution capabilities. A course resolution detector plane can be used to detect the Moiré patterns.

The Moiré patterns are then deconvolved. A stepped sine wave fitting can be used for this purpose. An inverse Fourier transform is also an option in the reconstruction of the image from the Moiré patterns. To use an inverse Fourier transform, two Fresnel zone plate pairs must be used. To get the cosine component of the transform, both plates must be identical where $r_n = r_1\sqrt{n}$. The other pair of plates will give the sine component if one plate has its zones defined by $r_n = r_1\sqrt{n}$ and the other plate is phase shifted by having its zones defined by $r_n = r_1\sqrt{(n-1/2)}$.

The major advantage of this system over one using a rotating modulation collimator is that the images produced are not time-averaged. The Moiré patterns are produced instantaneously, thus providing a "snapshot" of the sources. This is particularly useful in the study of solar flares where the source of X-rays changes in a short time.

Using a matrix of CsI scintillators coupled to photodiodes as the detector will provide the course position sensitivity required to provide images with sub-arcminute resolution. This type of detector will also provide good energy resolution.

Conclusion

This system is capable of providing images with sub-arcminute resolution and energy resolution. The images produced are not time-averaged. Due to the symmetry of the zone plates, the need for careful rotational alignment, as is necessary for the grids of rotational modulation collimators, is avoided. The use of CsI scintillators coupled to photodiodes reduces the weight and volume of the instrument considerably when compared to a similar system using photomultiplier tubes to view scintillators. This system will provide improved images over those provided by currently used systems and will do so with significant savings on bulk and weight.

References

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